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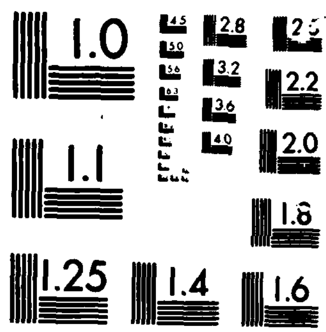

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SPACE-VARIANT OPTICAL SYSTEMS

Annual Technical Report

on

AFOSR Grant 84-0382

(Sept. 30, 1984 - Nov. 30, 1985)

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by

John F. Walkup and Thomas F. Krile
Co-Principal Investigators

January 1986

Optical Systems Laboratory

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Both analytical and experimental investigations of 1-D and 2-D coherent and incoherent space-variant optical processors have been conducted. The investigations included: (1) investigation of an improved measure of the degree of invariance of a linear system and its applications to piecewise isoplanatic space-variant systems; (2) a process for generalized linear filtering of 1-D signals; (3) investigation of a very fast architecture for performing optical multiplication of binary numbers and (4) techniques for both linear and nonlinear space-variant processing based on the bilinear transform.

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ABSTRACT

Both analytical and experimental investigations of 1-D and 2-D coherent and incoherent space-variant optical processors have been conducted. The investigations included: (1) investigation of an improved measure of the degree of invariance of a linear system and its applications to piecewise isoplanatic space-variant systems; (2) a process for generalized linear filtering of 1-D signals; (3) investigation of a very fast architecture for performing optical multiplication of binary numbers and (4) techniques for both linear and nonlinear space-variant processing based on the bilinear transform.

RESEARCH OBJECTIVES

The major research objectives during the first funding period (14 months) of the grant (September 30, 1984 - November 30, 1985) have been to perform both analytical and experimental work on optical implementations of space-variant optical processors. Both analog and digital computational operations have been investigated, and processors utilizing both coherent and incoherent illumination have been considered. The major areas of investigation have been (1) a complete investigation of piecewise isoplanatic space-variant systems and a new measure for the degree of invariance of linear optical processors, (2) a generalized filtering scheme for 1-D signals employing a phase information-preserving holographic recording technique, (3) an all optical technique for multiplying binary numbers with a high degree of parallel processing, and (4) techniques for performing both linear and nonlinear space-variant processing based on the bilinear transformation. Details are provided in the following sections.

SUMMARY OF RESULTS

Since most of the results obtained under the grant are promptly submitted for publication, and also presented at national and international scientific meetings, we will briefly summarize the major results obtained in this section, with references made to the appropriate publications, conference papers, and reports.

(1) Piecewise Isoplanatic Space-Variant Systems

It has previously been shown by our group that, for band-limited inputs, a space-variant linear system can be exactly characterized by knowledge of the sampled system point spread function and the corresponding sampled input [1,2]. Optical processors based on the sampling technique have, to date, encountered rather severe limitations in terms of input resolution, dynamic range and space-bandwidth product requirements for the system components. The implementation of space-variant optical processors based on the piecewise isoplanatic approximation (PIA) should alleviate some or all of these restrictions, since the PIA uses "coarse" sampling. The approximation employed divides the linear system input plane into isoplanatic patches to which corresponding point spread functions are assigned. The resulting PIA system output is an approximate representation of the true system output.

During this funding period, a new measure of the degree of invariance was developed as a tool to classify linear systems [3,4,5]. This new measure seems to predict the relationships

between the true and PIA system outputs better than the classical Lohmann and Paris measure [5-6]. With the aid of the new measure, we showed how to find the optimal size of each isoplanatic patch in the input plane and the optimal corresponding impulse response in each patch. Finally the relationship of the variation bandwidth to the new measure of invariance was studied and found to support the validity of the new measure.

(2) Generalized Linear Filtering of 1-D Signals

This project was completed during the funding period. Key developments were the use of a real-time holographic recording technique used at the output of a 1-D coherent space-variant processor [7-8]. In this recording scheme, the intensity of the sum of the filtered signal and an on-axis reference beam is integrated by a charge-coupled device (CCD) array. The bias term is subsequently removed electrically, yielding the desired signal term with amplitude and phase information preserved. Though some problems were encountered due a spatially-varying CCD array response, we believe these problems can be solved. One related result of interest is the ability of the processor to simulate the performance of parametric amplifiers. Experimental results were obtained demonstrating both space-invariant and space-variant applications. A Hilbert transform processor and a bandpass filter were two of the applications which were successfully demonstrated.

(3) Optical Multiplication of Binary Numbers

Continuing the research on optical space-variant processing techniques for numerical processing, new techniques for optical binary multiplication were investigated during this funding period [9-11]. The earlier approach of color-encoding the multiplier data and using feedback to convert from mixed binary to binary form at was found to require too many passes through the Hughes Liquid Crystal Light Valve and was consequently too slow. A new approach was taken which first forms all the partial products simultaneously in parallel. We then regroup the bit products, thereby obviating the necessity of the "shift" operation. Finally we optically perform carry look-ahead addition of the resulting binary words to get the final product. The number of intensity levels is restricted to three, as before, preserving the noise immunity and thus providing high accuracy. The multiplier and multiplicand bits, encoded in bright true logic, are introduced in bar-shaped patterns onto the WRITE and READ sides of a Hughes LCLV. The analyzer is kept crossed with respect to the direction of polarization of the incoming beam. The AND operation performed results in the formation of an array of partial products. The bit products are then regrouped diagonally to form new binary words. Entire partial products need no longer be shifted in this case. These binary words are then added to get the final product. An algorithm for optical carry look-ahead addition was conceived, and implemented in an optical arrangement which produces all the carries in essentially one switching time. Proof-of-principle experiments were conducted to (a) form the

array of partial products and (b) generate the carries. These experiments confirmed the validity of the new techniques. The proposed system offers a better solution to the problem of the propagation of carries than earlier approaches utilizing residue arithmetic. It performs a multiplication in only 13 switching times of the LCLV. It utilizes the spatial parallelism of optical systems to perform a number of multiplications and additions in parallel, and thus could become the processing unit of a very fast optical matrix multiplier.

(4) Bilinear Space-Variant Processing

A. Introduction

During this past year, we have investigated extensions of our previous space-variant work to the new area of 2-D nonlinear space-variant processing. In particular, we concentrated on potential applications in the area of optical computing. As a start, we investigated the simplest nonlinear system, i.e. the bilinear space-variant system. As a result, a general mathematical model was developed, several optical implementation techniques were designed, and a number of application areas were studied [12].

B. Mathematical Formulation

A 1-D bilinear space-variant operation can be described by

$$g(y) = \iint_{-\infty}^{\infty} h(y;x',x'')\, f'(x')\, f''(x'')\, dx'\, dx'',$$

where f' and f" are two inputs, g is the output and h is the kernel of the system. This equation is also known as the bilinear transform. A characteristic of this transform is that if one of the inputs is fixed, then the transform becomes a generalized linear transform. The properties of this bilinear operator have been studied, resulting in a new set of space-variant system classifications. This added "richness" to the class of space-variant systems gives rise to new implementations and applications in the area of optical computing.

C. Implementations

1. Using 2-D linear space-variant processors.

We have shown that if we use the output of a 2-D linear space-variant processor which lies on a 45° line with respect to both output axes, change the 4-D kernel into 3-D kernel and apply two inputs on the orthogonal axes of the input plane, a 1-D bilinear transform is realizable.

2. Phase grating technique with a liquid crystal light valve (LCLV).

By using LEDS (input f"(x")) at different locations, each LED can produce a different spatial grating on the "WRITE" side of the LCLV (if a reference beam is added). Based on performing the AND operation on the LCLV, the input f'(x') on the "READ" side of the LCLV will be imaged at different output locations where we place different space-variant holograms (e.g. multifaceted holograms). In this way a 2-D bilinear transform is achievable.

3. Acoustooptical processor

Consider the light incident on an acoustooptical cell as the first input $f'(x')$, and the electronic signal input to the acoustooptical cell as the second input, $f''(x'')$. By frequency modulation and spatial modulation of the acoustooptic cell, any combinations of two inputs will be deflected to different output locations where holograms (kernels) are placed. With this system a 1-D real-time bilinear transform can be performed. Using a multichannel acoustooptical cell will improve the space-bandwidth product requirements.

D. Applications

A bilinear transform in discrete form can be represented by a triple vector-matrix-vector product, i.e.

$$g(y) = \sum_{n=1}^{N} \sum_{m=1}^{M} f'(n)\ h(y;n,m)\ f''(m)$$

$$= \underline{f}'^{T}\ H\ \underline{f}''$$

where H is a matrix, $\underline{f}'$ and $\underline{f}''$ are two column vectors and T represents the transpose operator.

1. Programmable optical interconnection [1]

By using $\underline{f}''$ as a control input and $\underline{f}'$ as a signal input, the bilinear transform can be made to perform programmable optical interconnections. By changing the control input, the system can provide various mappings between signal input and output. This approach offers a great flexibility in logic design, since tens or hundreds of operations can be performed using afixed system.

2. 2-D Cross-bar

Let H be a 2-D input, and let $\underline{f}'$ and $\underline{f}''$ be two control inputs in the two orthogonal dimensions, respectively. By changing the control inputs, each entry of H can be mapped to different locations in a 2-D output plane. Furthermore, a 2-D crossbar can be performed in real time if real-time SLMs (such as the magneto-optic LIGHT-MOD) are used to replace the two control inputs $\underline{f}'$ and $\underline{f}''$.

3. Triple-product Processing

The discrete bilinear transform can be extended to triple matrix-matrix-matrix products, ie., $g(y) = F' \, H \, F''$. Here F', F'', and H'' are all considered signal inputs. This triple product processing is useful in image processing. It can also be used to implement a generalized eigensystem if feedback is considered.

Secondly, we can use triple-product processing to implement logic designs for either combinatorial or sequential circuits. This processor can also operate in an MIMD (multiple instructions multiple data) format.

4. Bilinear space-variant processing

Here, f' and f" are signal inputs and H is the system kernel. The linear transform is a special case of the bilinear transform. Therefore, several linear transforms such as convolution and correlation can be processed in a fixed bilinear system. Again it is quite powerful since the system is fixed, but several operations can be performed.

At this stage the LCLV implementation has been set up and tested in the lab and the A-O modulator implementation will have been tested in another month. In terms of applications, the programmable optical interconnections and the triple-product processor used to implement combinatorial logic have both been tested with good results.

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2. R. J. Marks II, J. F. Walkup and M. O. Hagler, "Sampling Theorems for Linear Shift-Variant Systems," IEEE Trans. on Circuits and Systems, 25, 228 (1978).

3. S. H. Lin, "Piecewise Isoplanatic Approximation in Space-Variant Processing," M.S.E.E. thesis, Electrical Engineering Dept., Texas Tech University, May, 1985.

4. S. H. Lin, T. F. Krile, and J. F. Walkup, "Piecewise Isoplanatic Modeling of Space-Variant Linear Systems," submitted to JOSA-A, Nov. 1985.

5. S. H. Lin, T. F. Krile, and J. F. Walkup, "Piecewise Isoplanatic Modeling of Space-Variant Linear Systems," Opt. Soc. of Am. Annual Mtg, Washington, D. C., October, 1985.

6. A. W. Lohmann and D. P. Paris, "Space-Variant Image Formation," J. Opt. Soc. Am., 55, 1007 (1965).

7. L. A. Blanchard, M. O. Hagler, T. F. Krile, J. F. Walkup, "Generalized Real-Time One-Dimensional Linear Filtering," J. Opt. Soc. Am. -A, 1, 1264A, 1984 (Paper presented at 1984 Annual Mtg., Optical Soc. of America, San Diego, October, 1984).

8. L. A. Blanchard, "Generalized Optical Linear Filtering of One-Dimensional Signals," M. S. thesis, Dept. of Electrical Engineering/Computer Science, Texas Tech University, August, 1985.

9. N. A. Patkar, T. F. Krile, J. F. Walkup, "Real-Time Binary Multiplication by Optical Methods," J. Opt. Soc. Am.-A, 1, 1257A, 1984. (Paper presented at 1984 Annual Mtg., Optical Society of America, San Diego, October, 1984).

10. V. Chandran, N. Patkar, T. F. Krile and J. F. Walkup, "Digital Optical Multiplication by Color Multiplexing," Topical Meeting on Optical Computing, Technical Digest, Incline Village, NV, March, 1985.

11. V. Chandran, "Techniques for Optical Binary Multiplication," M. S. thesis, Dept. of Electrical Engineering/Computer Science, Texas Tech University, December, 1985.

12. S. H. Lin, T. F. Krile and J. F. Walkup, "Programmable Optical Interconnections Based on the Bilinear Transformation," SPIE Proceedings, Vol. 625, Los Angeles, CA, January, 1986.

RECORD OF JOURNAL PUBLICATIONS ON AFOSR 84-0382*

Journal Articles in Press

1. V. Chandran, T. F. Krile, J. F. Walkup, "Optical Techniques for Real-Time Binary Multiplication", (to appear in Applied Optics feature issue on optical computing, July 15, 1986).

2. S. H. Lin, T. F. Krile, J. F. Walkup, "Piecewise Isoplanatic Modeling of Space-Variant Linear Systems," (Submitted to J. Opt. Soc. Am.-A, 1985).

Journal Articles in Preparation

1. S. B. Chase, T. F. Krile, J. F. Walkup, "Simple Tests for Binary Phase Mask Quality" (to be submitted to Optical Engineering).

2. S. H. Lin, T. F. Krile, J. F. Walkup, "Optical Triple-Product Processing in Logic Design" (submitted to feature issue of Applied Optics, R. Bocker, Ed., 1986).

* Papers appearing in published meetings proceedings listed under "Interaction Activities."

RESEARCH PERSONNEL (1984-1985)

(1) Faculty:

Dr. J. F. Walkup, Co-Principal Investigator, Horn Professor

Dr. T. F. Krile, Co-Principal Investigator, Associate Professor

Dr. M. O. Hagler, Research Associate, Horn Professor

(2) Graduate Students

L. A. Blanchard
G. Spillman
S. H. Lin
V. Chandran

(3) Undergraduate Laboratory Assistants

J. Hartley
B. Jones
R. Bashir

COMPLETED THESES AND DISSERTATIONS (1984-1985)

1. S. H. Lin, "The Piecewise Isoplanatic Approximation in Space-Variant Processing," M.S. thesis, Dept. of Electrical Engineering/Computer Science, Texas Tech University, May 1985.

2. L. A. Blanchard, "Generalized Optical Linear Filtering of One-Dimensional Signals," M. S. thesis, Dept. of Electrical Engineering/Computer Science, Texas Tech University, August, 1985.

3. V. Chandran, "Techniques for Optical Binary Multiplication," M. S. thesis, Dept. of Electical Engineering/Computer Science, Texas Tech University, December, 1985.

INTERACTION ACTIVITIES (1984-1985)

Papers Presented at Major National Technical Meetings:

(1) D. Y. Lojewski, J. F. Walkup, T. F. Krile, "Space-Variant Optical Processing with Acousto-Optic Modulators," J. Opt. Soc. Am.-A., 1, 1230A, 1984. (Paper presented at 1984 Annual Mtg, Optical Society of America, San Diego, October, 1984).

(2) L. A. Blanchard, M. O. Hagler, T. F. Krile, J. F. Walkup, "Generalized Real-Time One-Dimensional Linear Filtering," J. Opt. Soc. Am.-A, 1, 1264A, 1984. (Paper presented at 1984 Annual Mtg., Optical Society of America, San Diego, October, 1984.

(3) N. A. Patkar, T. F. Krile, J. F. Walkup, "Real-Time Binary Multiplication by Optical Methods," J. Opt. Soc. Am.-A, 1, 1257A, 1984. (Paper presented at 1984 Annual Mtg., Optical Society of America, San Diego, October, 1984).

(4) V. Chandran, N. Patkar, T. F. Krile and J. F. Walkup, "Digital Optical Multiplication by Color Multiplexing," Topical Meeting on Optical Computing, Technical Digest, Incline Village, NV, March, 1985.

(5) S. H. Lin, T. F. Krile, J. F. Walkup, "Piecewise Isoplanatic Modeling of Space-Variant System," J. Opt. Soc. Am.-A, 2, p. 8, 1985. (Paper presented at 1985 Annual Mtg., Optical Society of America, Washington, D.C., October 1985).

(6) V. Chandran, T. F. Krile and J. F. Walkup, "Optical Techniques for Binary Matrix-Vector Multiplication," J. Opt. Soc. Am-A, 2, p. 14, 1985 (Paper presented at 1985 Annual Mtg., Optical Society of America, Washington, D.C., October 1985).

Other Interaction Activities

1. Visited Prof. Sing H. Lee's research Laboratory at University of California-San Diego, October, 1984 (J. F. Walkup, T. F. Krile, and graduate students).

2. Briefed Dr. Lee Giles in Washington, D. C., Fall 1985 (J. F. Walkup).

3. Presented invited paper on "Nonlinear Image Restoration in Signal-Dependent Noise' at SPIE O-E LASE '85 Mtg. in Los Angeles, January 1985 (J. F. Walkup co-author).

4. Served as Chairman of IEEE Computer Society's Technical Committee on Optical Processing 1984-1985 (J. F. Walkup).

5. Served on Education Committee of Optical Society of America and Educational Policy Committee of American Institute of Physics (J. F. Walkup).

SIGNIFICANT ACCOMPLISHMENTS

1. Developed an improved measure of the degree of invariance of linear optical systems.

2. Developed a real-time holographic CCD recording technique for preserving phase information when using intensity-sensitive detectors.

3. Investigated a fast, highly parallel architecture for optical multiplication of binary numbers.

4. Developed techniques for programmable optical interconnections based on the bilinear transformation.

5. Investigated an optical triple-product processor based on a generalization of the bilinear transform.

6. Investigated a 2-D optical cross-bar switch based on the bilinear transformation.

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